# Generation of high-flux neutron beam from radiation pressure driven deuterium ion bunches

# Generation of High-Flux Neutron Beam from Radiation Pressure driven Deuterium Ion Bunches

A. Alejo[1], S. Kar[1*], H. Ahmed[1], A.G. Krygier[2], R. Clarke[3], R.R. Freeman[2], J. Fuchs[4], A. Green[1], J.S. Green[3], D. Jung[1], A. Kleinschmidt[5], J.T. Morrison[6], Z. Najmudin[7], H. Nakamura[7], P. Norreys[3,8], M. Notley[3], M. Oliver[8], M. Roth[5], L. Vassura[4], M. Zepf[1], M. Borghesi[1]

[1]*Centre for Plasma Physics, Queen's University Belfast, BT7 1NN, UK*

[2]*Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*

[3]*Central Laser Facility, Rutherford Appleton Laboratory, Didcot, Oxfordshire, OX11 0QX, UK*

[4]*LULI, Ecole Polytechnique, CNRS, Route de Saclay, 91128 Palaiseau Cedex, France*

[5]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

[6]*Propulsion Systems Directorate, Wright Patterson Air Force Base, Ohio 45433, USA*

[7]*Blackett Laboratory, Department of Physics, Imperial College, London SW7 2AZ, UK*

[8]*Department of Physics, University of Oxford, Oxford, OX1 3PU, UK*

An ultra-short burst of fast neutrons has a wide range of applications in science, industry, healthcare and security. However, the limitation in accessing large facilities has led to an increasing interest in finding a table-top sources. Laser-driven ion accelerators have been investigated as a possible solution[1], mainly by using the ions accelerated via the Target-Normal Sheath Acceleration (TNSA)[2] mechanism impinging on suitable neutron converter targets. Despite of being a robust mechanism, TNSA exhibits a slow ion energy scaling with respect to the incident laser intensity ($E_{ion} \propto \sqrt{I_L}$), with a beam predominantly formed by protons, reducing the range of possible nuclear reactions involved in the neutron generation.

Here we report on the neutron generation using radiation-pressure driven ion acceleration (RPA) [3]. This mechanism holds the advantage of generating higher energy ion beams, including heavy ions, with high laser-ion conversion efficiency and low divergence. Unlike typical experiments, where a secondary converter target is needed, a high-flux, directional neutron beam was produced from the primary target itself when RPA mechanism is involved.

## Experimental Setup

The experiment was carried out at the Rutherford Appleton Laboratory (RAL), STFC, UK by employing the petawatt arm of the VULCAN laser (wavelength ($\lambda$)=1053nm) system. A

*s.kar@qub.ac.uk

schematic of the experimental setup is shown in Fig. 1, where the laser is focussed on the target foil at normal incidence by an $f/3$ parabola down to a $\sim 5$ µm spot, delivering a total energy of $100-250$ J on the target in $850 \pm 150$ fs pulses and leading to a peak intensity ($I_0$) on the target in the range $(1-3) \times 10^{20}$ W cm$^{-2}$. The targets were made of deuterated plastic ($(C_2D_4)_n$) with thickness in the range $l = 90-900$ nm and 10µm. The ions accelerated during the interaction were diagnosed using five Thomson Parabola Spectrometers (TPS). Due to the overlapping traces of other ion species with similar charge-to-mass ratios ($C^{6+}$, $O^{8+}$), differential filtering technique [4] was implemented to obtain the full spectrum of deuterons. The neutrons generated from the laser irradiated target were diagnosed along the laser axis and $\sim 135°$ off axis by using absolutely calibrated fast plastic scintillator detectors[5] in time-of-flight (nToF) configuration, shielded against Bremsstrahlung and $\gamma$ radiations by $\sim 5$ cm of lead.

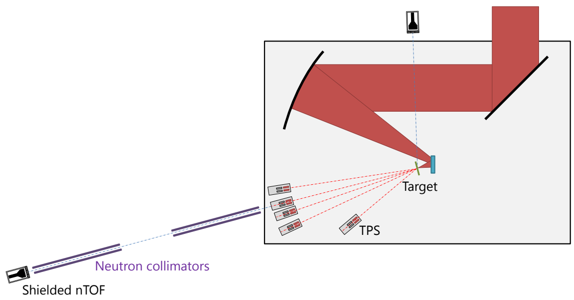


Figure 1: *Experimental setup*

**Neutron generation**

Most of the efforts regarding the generation of a bright, directional neutron beam have been focussed on the use of a pitcher-catcher configuration, in which the laser-driven ions impinge in a secondary target, where the nuclear reactions take place. The need of such double-target setup arises from the fact that the laser irradiated targets produce low flux neutrons isotropically. In order to compare the neutron generation from the laser-target interaction itself depending on the underlying mechanism, both the neutron and ion spectra where recorded for a series of shots, where CD-foil targets varied between 90nm and 10µm thick while keeping the laser conditions as constant as possible.

As expected from the TNSA mechanism, quasi-exponential ion spectra were obtained from the irradiation of thick targets (10µm) as shown in Fig. 2(a). Since the TNSA mechanism favours acceleration of highest charge-to-mass ratio ion species (protons supplied by the hydrocarbon contamination layer on the target surface), a non-efficient acceleration of the deuterium ions (upto a maximum energy of $\sim$5 MeV/nucleon) was observed in this case. However, when the target thickness was reduced to hundreds of nanometres, narrow-bandwidth spectral features appeared towards the high energy end of the deuteron spectra, with significant increase in cut-off energy. Such spectral behaviour for heavy ions from ultra-thin targets has been previously reported by Kar *et al.* [3], attributing to the onset of RPA-LS mechanism in a TNSA hybrid regime. Finally, a further reduction in the target thickness to 90nm led to disappearance of the bunched structure, despite of the increase in deuteron cut-off energy.

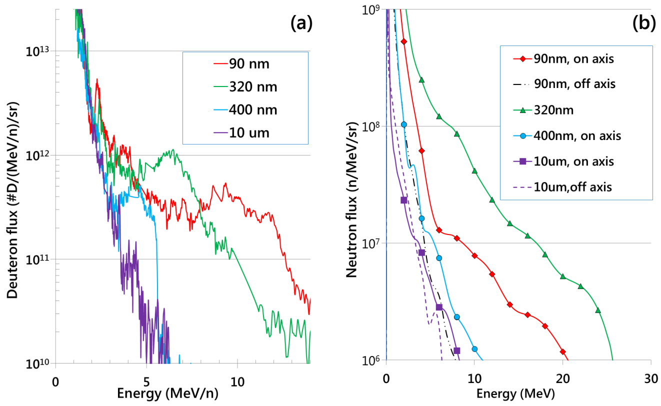


Figure 2: *(**a**) Appearance of narrow-bandwidth features in the deuterium spectra. (**b**) Variation of the neutron spectrum depending on the target thickness.*

A comparison between the neutron spectra obtained for different target thickness is shown in Fig. 2(a). For clarity, the off-axis spectra were only included for the two extreme thicknesses, showing how the emission at that angle was similar for all the targets. As expected for thick targets (10µm), where the energetic ions are driven by TNSA with an exponential energy spectra and large divergence (Fig. 2a), an isotropic, low-flux emission of neutrons was measured. In this case the neutrons are produced most likely at the target front surface due to the ions driven by hole-boring mechanism impinging the bulk of the target. However, as the thickness of the target was reduced to the RPA range, a substantial improvement in on-axis neutron flux was observed, which led to an increase in neutron energy and beam anisotropicity, as the off-axis emission remained constant. Finally, a large drop in the neutron flux was measured when the thickness was further reduced to 90nm. It is interesting to note here that the increase in neutron flux doesnot correlate to the increase in ion energy. Therefore the enhancement in neutron flux must relate to the conditions during the ion acceleration.

In order to explain the increase in flux when the RPA range is approached, as well as the eventual drop, a plasma cylinder model can be considered, in which neutron yield is given by

$$Y_n \simeq \frac{\tau_{burn}}{2} \int n_d^2 \langle \sigma v \rangle \, dV \tag{1}$$

where, $n_d$ is the deuteron number density interacting for an interval $\tau_{burn}$, called fusion burn time, and $\langle \sigma v \rangle$ is the velocity averaged fusion reactivity. With such model, the high neutron flux generated in the RPA case can be explained in terms of the high deuterium density ($n_d$) within the simultaneously-accelerated bunch, explaining the increase with respect to the TNSA/HB case. Nevertheless, a further reduction of the thickness can lead to the so-called Self-Induced Transparency, either due to relativistically induced transparency or a drop in the density following the target expansion. In such case, the bunch structure will promptly disappear, which explains the ion spectra for 90nm in Fig.2a. Also, the large drop in the interacting time of the ions reflects in the plasma cylinder model as a reduction of the burning time, which in turn explains the low efficiency in neutron generation in that case.

To substantiate the observed drop in efficiency for ultrathin targets, 2D PIC simulations were performed using the EPOCH code. Due to the limited computational resources, the parameters of the laser-plasma interaction were scaled down maintaining $I_0/c^3$ and $a_0^2\tau_p/\chi$ constant. When the 320nm foil is used (Fig. 3a,b), the laser beam is still reflected on the target surface, allowing for an optimum LS acceleration, with only a minor part of it travelling through as a consequence of an evanescent wave being able to reach the back of the thin target. However, when the thickness is further reduced to 90nm, the target becomes fully transparent rapidly before the laser reaches its peak intensity, as it can be seen from the electric field travelling through the plasma (Fig. 3c), leading to the heating of the whole plasma and removing the bunched-structure (Fig. 3d).

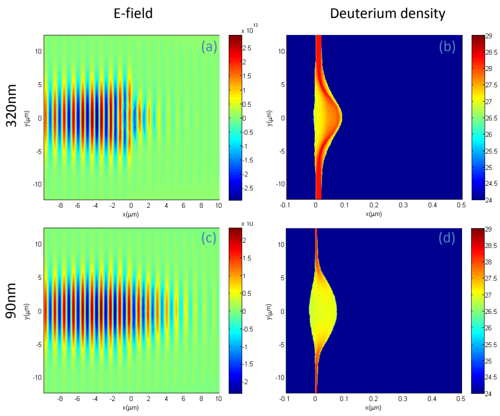

Figure 3: *Simulation results*

## Conclusion

The cohesive acceleration of ion bunches during the LS phase is underpinned implicitly by the observed increase in neutron flux and anisotropy, so as by the observation of abrupt drop in neutron generation with sufficiently thin targets, most likely becoming relativistically transparent. The neutron spectroscopy of the interaction was not only an useful diagnostic to understand and optimise the ion acceleration mechanism, but neutron generation from the LS driven ion bunches has been found to be an efficient route to produce a compact laser-driven neutron source, alternative to traditionally used neutron converters in front of the laser irradiated target.

## References

[1] K. Lancaster et al., Phys. Plasmas, **11**, 3404 (2004)
[2] S. Wilks et al., Phys. Plasmas, **8**, 542 (2001).
[3] S. Kar et al., Physical Review Letters **109**(18) (2012)
[4] A. Alejo et al., Review of Scientific Instruments **85**(9) (2014)
[5] S.R. Mirfayzi et al., Review of Scientific Instruments **86**(7) (2015)